

Delivering GNSS Algorithms and Data as a Fourth Observation for Local Tsunami Warning

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2. Scripps Institute of Oceanography, La Jolla, CA

3. Central Washington University, Ellensburg, WA



Our Goals



Leverage NASA research investments in

- Real-time GNSS (global navigation satellite system) point positioning
- Earthquake early warning
- Tsunami early warning to augment the speed and accuracy of the NOAA National and Pacific Tsunami Warning Centers (NTWC and PTWC) response process.

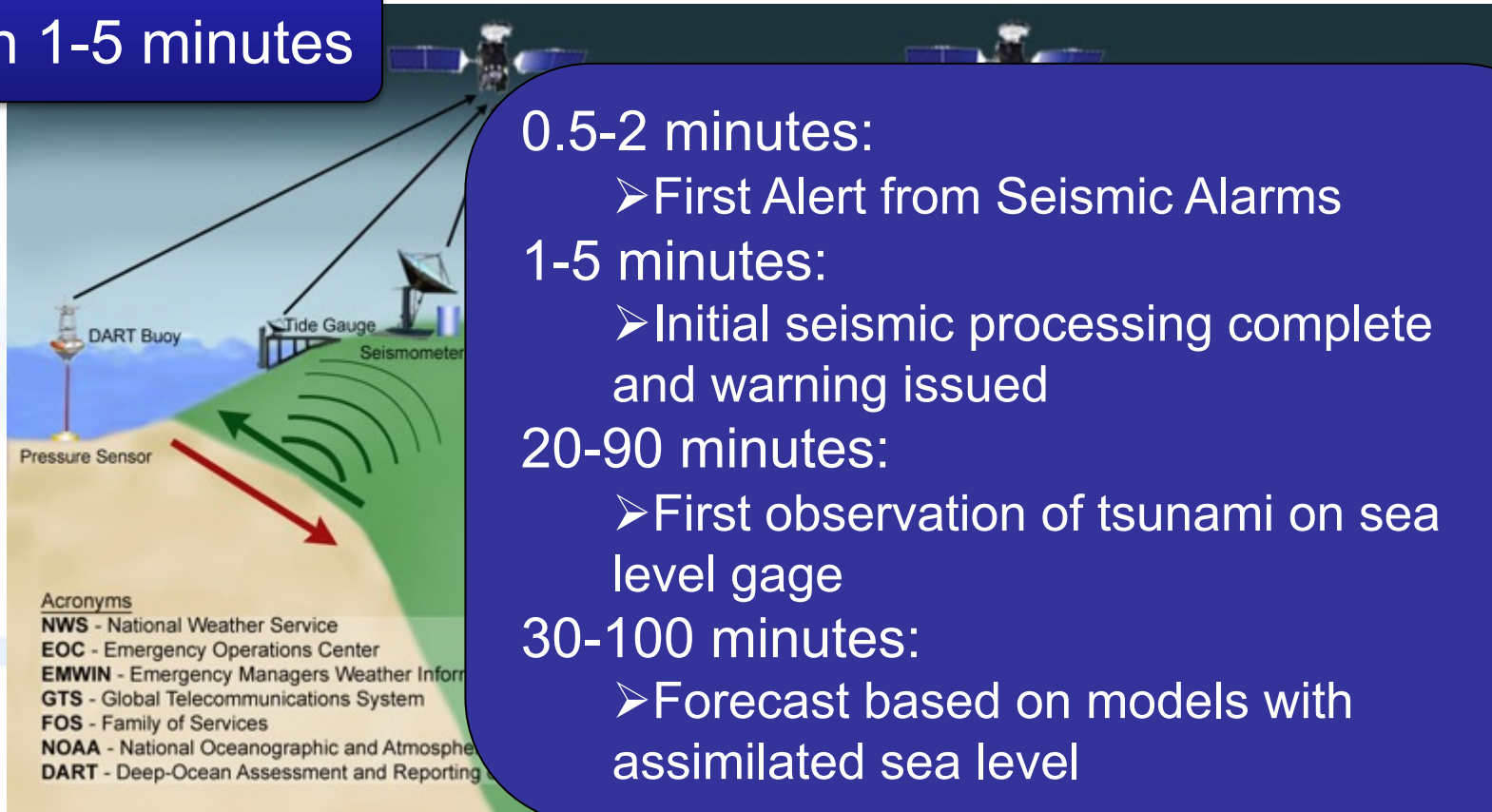
Advance readiness toward application

- Demonstration of integrated and collaborative science and technology
- Evaluation and Testing with end users
- Transition of research results to operational applications (*R2A*)

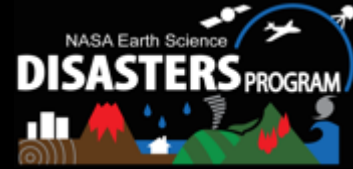
How Tsunami Warning Works



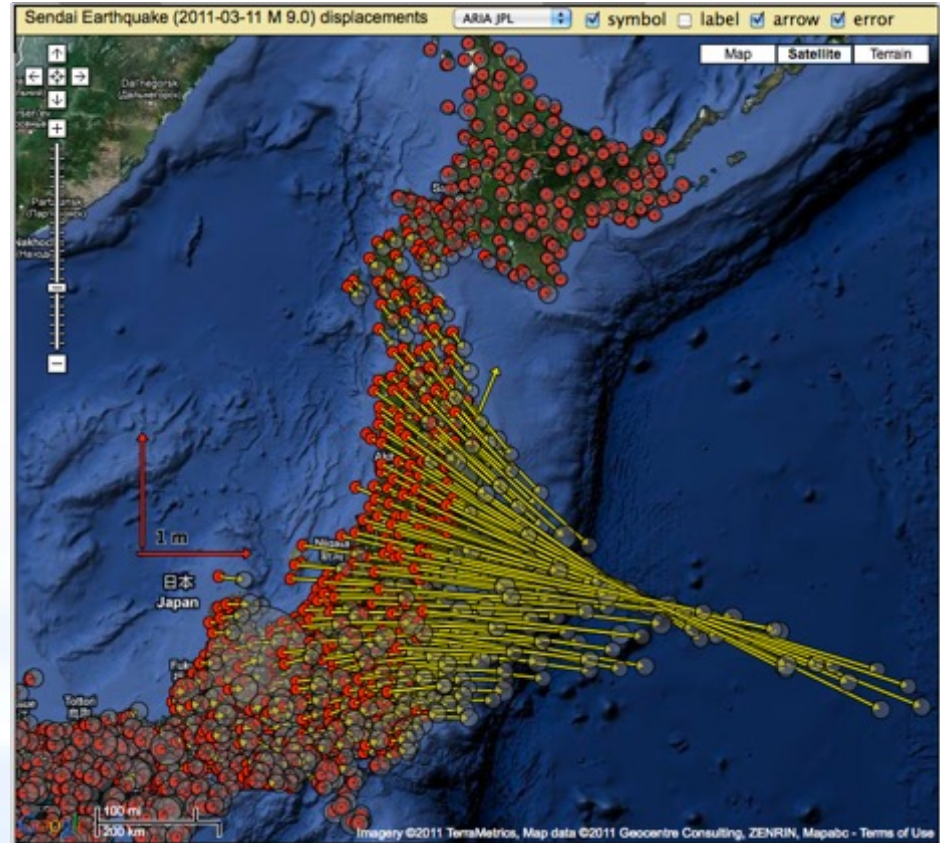
...in 1-5 minutes



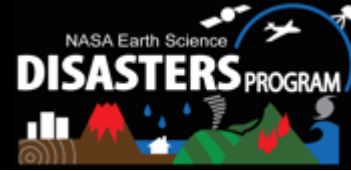
Augmenting Tsunami Warning with GNSS



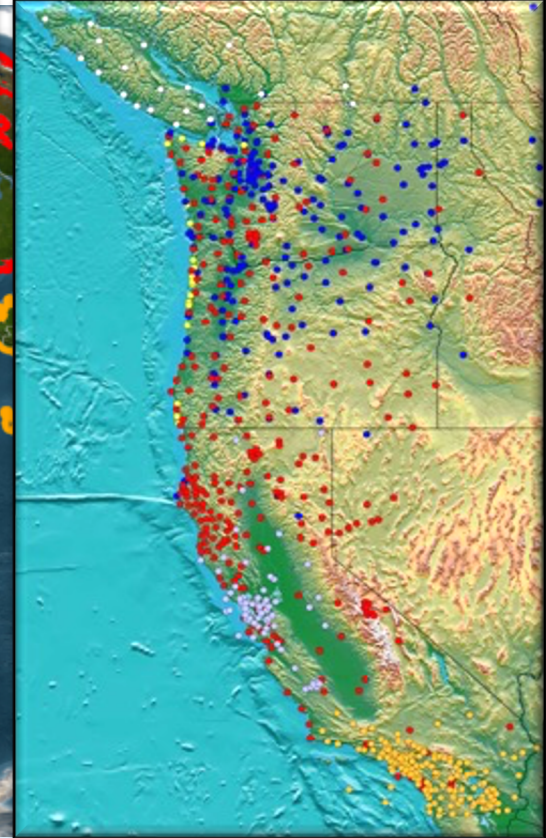
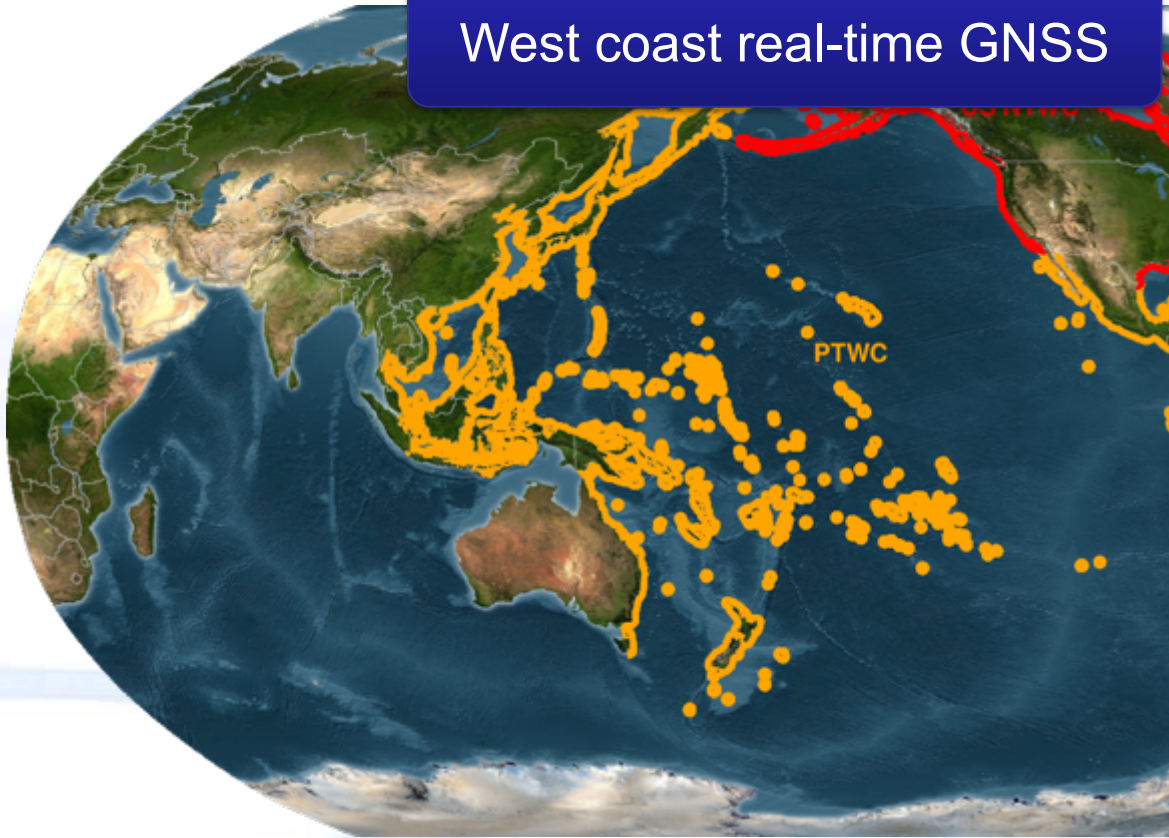
- Geodetic methods speed up earthquake magnitude and location estimates for large, local earthquakes
- Can provide information about faulting and ground deformation
- Can inform tsunami risk by understanding the change in the coastline and ocean floor



NOAA Tsunami Warning Centers

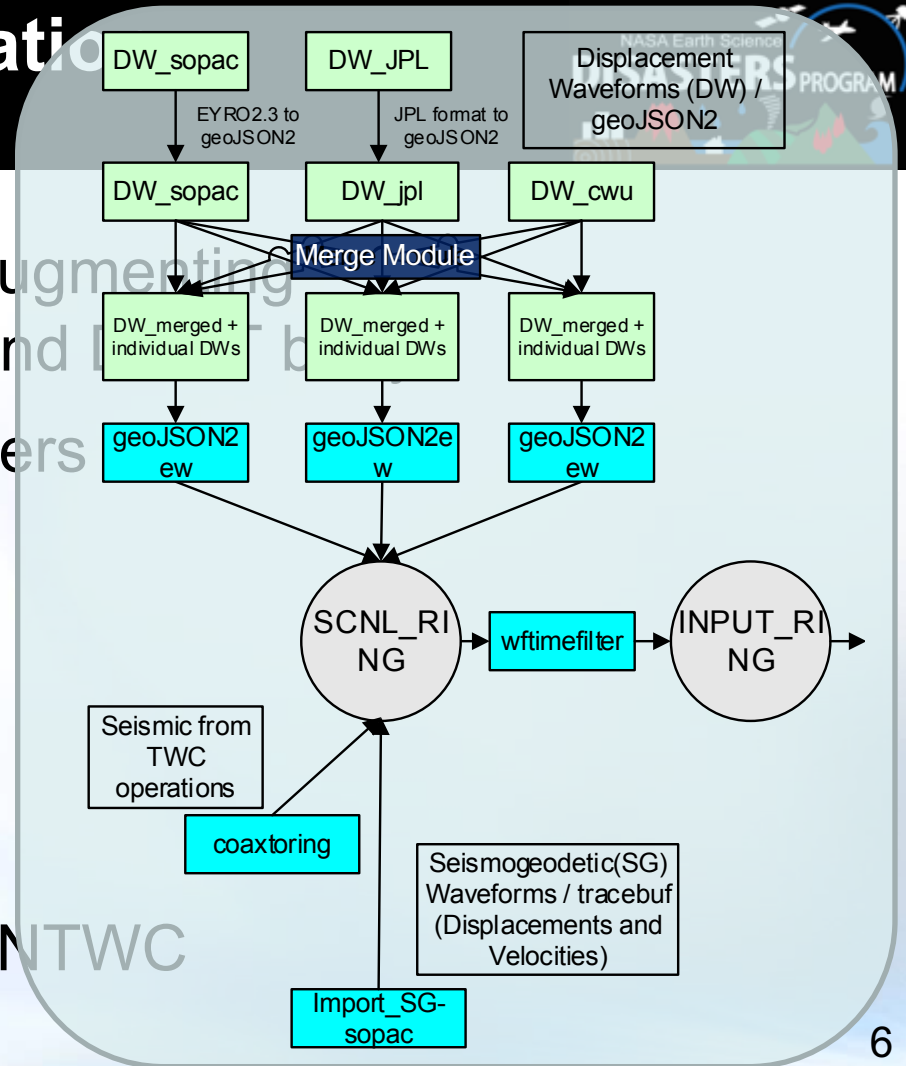


West coast real-time GNSS



Integrating a Novel Observation for Tsunami Warning

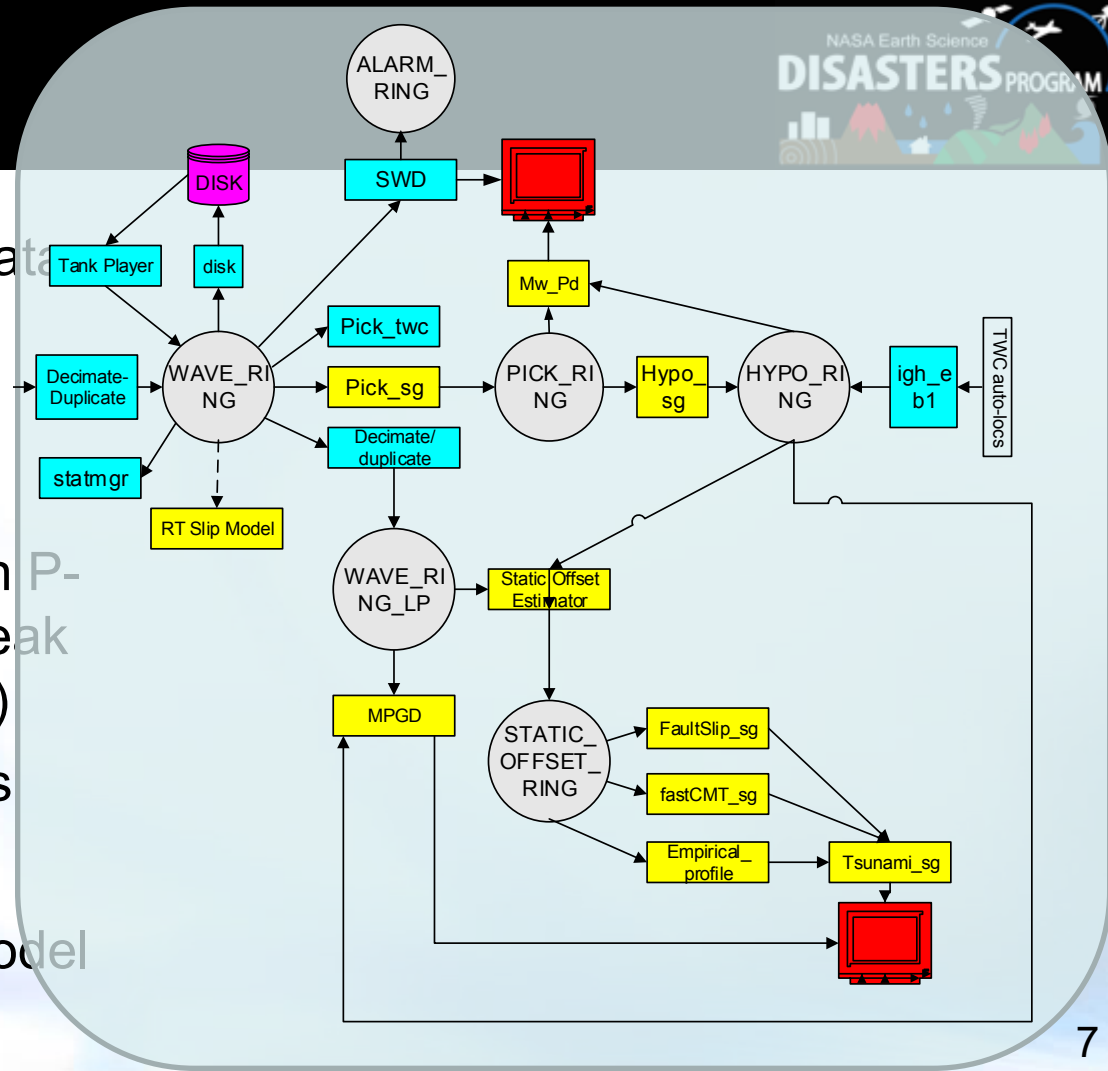
- **GNSS** is a 4th observation augmenting seismometers, tide gauges, and
- GNSS Data from Three Partners
- Redundant Merged Streams
- Standard Message Passing
- Seismogeodetic Data
- Earthworm Compatibility
- Delivered to both PTWC and NTWC



New Data need New Algorithms

GNSS and Seismogeodetic Data
Require Updated Algorithms

- P-wave picking
- Hypocenter estimation
- Magnitude scaling based on wave amplitude (Pd) and peak ground displacement (PGD)
- Finite-source CMT solutions
- Static fault slip models
- Tsunami source function model



Current Status

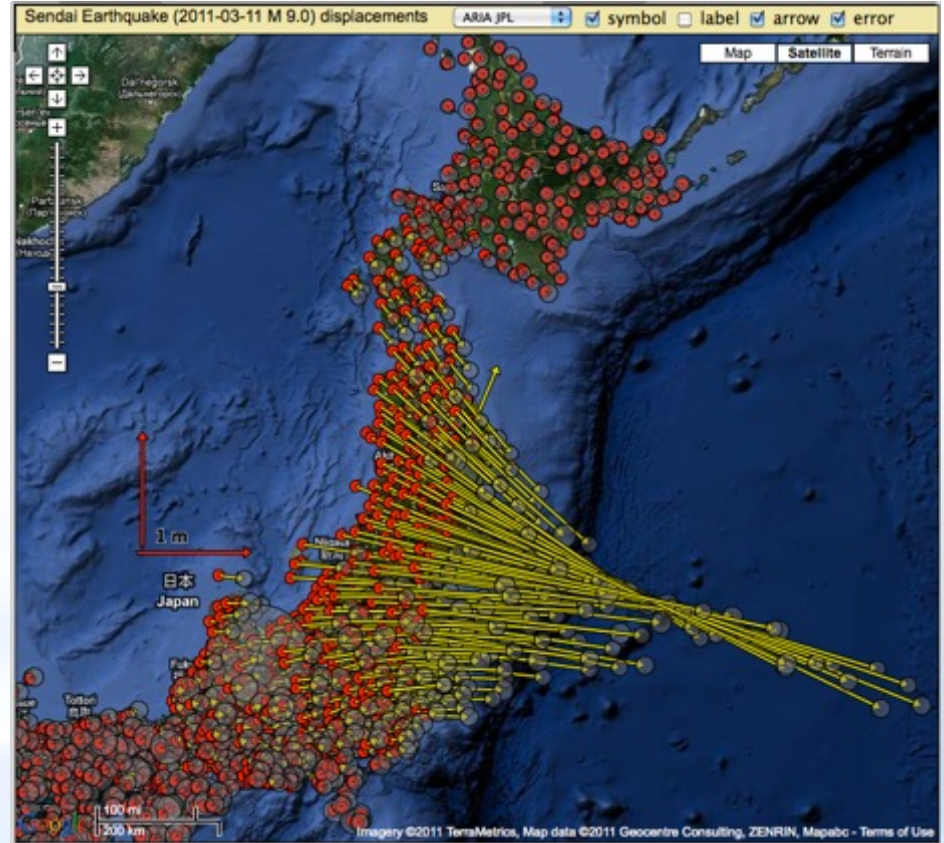
- Data architecture is streaming and merging data from all centers
- Merging algorithm upgraded to reduce spikes and improve data when one source is missing
- GNSS algorithm modules are being delivered and installed at TWCs

Next Steps

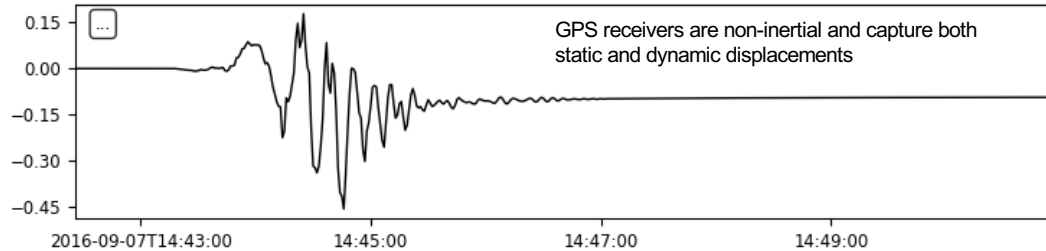
- Complete installation and testing algorithms at NTWC and PTWC
- Perform end-to-end testing with recorded and simulated events
- Add more real-time GNSS stations

Static Offsets

- Simply visualizing the GNSS offsets give important information
- Watch-standers can use this information to gauge the severity of the event



MwPGD (Magnitude from Peak Ground Displacement)



- The peak ground displacement is simply the max distance the station moves:

$$\text{PGD} = \max \left(\sqrt{N(t)^2 + E(t)^2 + U(t)^2} \right)$$

where N , E , and U are the 3 components of displacement

- Magnitude is estimated via the following empirical relation:

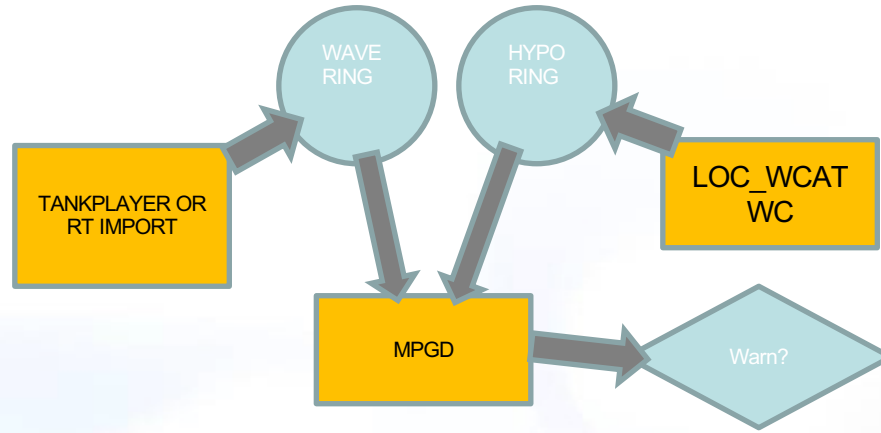
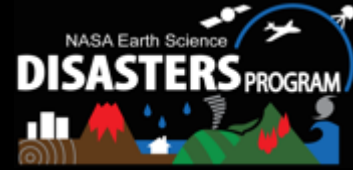
$$\log(\text{PGD}) \approx A + B M_{pgd} + C M_{pgd} \log(r)$$

where r is the source-receiver distance

A rapid, non-saturated mag calculation! Perfect for tsunami warning!

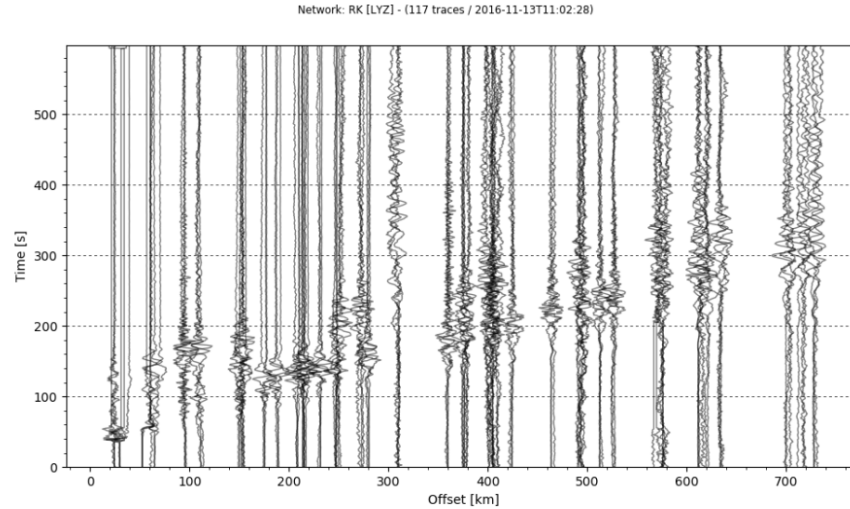
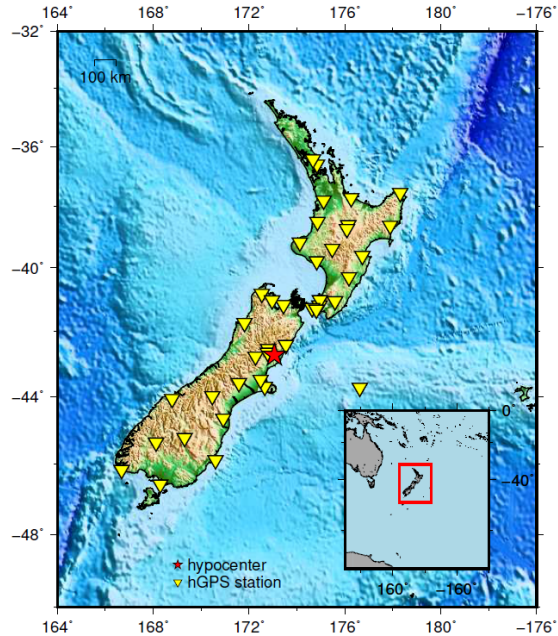
(Crowell, *et al.*, 2013, Melgar, *et al.*, 2015)

MwPGD Earthworm Module



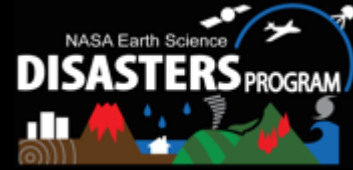
- Both NTWC and PTWC rely heavily on Earthworm for real-time data acquisition and processing
- MwPGD has been coded into an Earthworm module for operational use
- Calculation is triggered by hypocentral parameters derived from seismic. This hypo is determined quickly!
- Module tested with the Tankplayer tool to simulate a real-time environment.

Data Example (retrospectively)



- 2016 Kaikoura M7.8 event
- Hypo from seismic in ~4 min
- **MwPGD 7.9 in 8 minutes from o-time**

Lessons Learned



- Bring Research and Operational teams together in the beginning
- Identify a limited subset of initial data
- Agree on an initial set of algorithms
- Address the complexity of integration with specialized resources
- Evaluate applications in the operational environment (testbed) to build trust

Program Goals



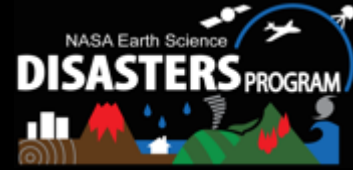
- Create and leverage partnerships among researchers, developers and operational end users
- Enable collaborative evaluation and testing, co-development, integrated planning and program management
- Promote access and availability to critical low-latency data sources characterizing areas of highest risk
- Support unique and urgent opportunities to harvest mature research results, applications, and technologies
- Recognize that Research to Applications requires collaboration around shared objectives and takes considerable time and targeted resources

Acknowledgements



- NASA Earth Science
 - Research and Analysis, Technology, and Missions
- NOAA National Weather Service
 - National and Pacific Tsunami Warning Centers
- NASA Applied Science - *is what we're all about!*
 - Transition of NASA Earth Science & Technology to end users
- ROSES RRNES
 - Cooperative agreement for Rapid Response and Novel Research in Earth Science

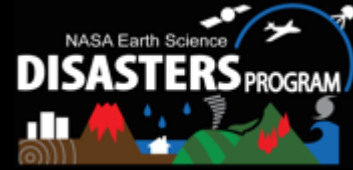
NASA Funded Contributors



- **Scripps Institution of Oceanography**
Yehuda Bock
 - Seismodeogetic Sensors
 - GNSS Processing
- **NASA Jet Propulsion Lab**
Yoaz Bar-Sever, Tony Song
 - Global Differential GPS (GDGPS) Network/Processing
 - Tsunami Source Function Estimation
- **University of Oregon**
Diego Melgar
 - Historic Data
 - *Fakequake* Scenarios
- **Central Washington University**
Tim Melbourne
 - GNSS Processing
 - Communication/Merging

BACKUP SLIDES

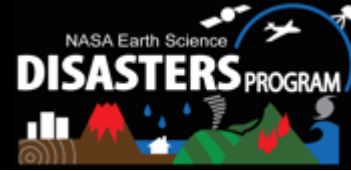
A New Approach ! Research to Application (R2A)



- Team Building with Program Management
- Intensive and Tactical Webinar and Face-to-face Meeting Series
 - Gained shared understanding of mature research results, available technologies, data access, operational process, and operational system opportunities
 - Enabled collaborative design
 - Committed to integrated plans and implementation objectives
- Rapid Response Funding – unique and timely
- On-going Commitment and Engagement

Bringing Researchers to Operations

NTWC, Palmer, AK



- Shared understanding of an Operational Tsunami Warning Center process
 - Quick Response Dominates
 - State of the Art is Hands-on
 - Where does GNSS Fit In?
- Develop an Architecture
 - Data and Functionality
 - Module Design
- Integration Plan
 - Testbed to evaluate capabilities and transition



Tsunami Response Timeline



0.5-2 minutes:

- First Alert from Seismic Alarms

1-5 minutes:

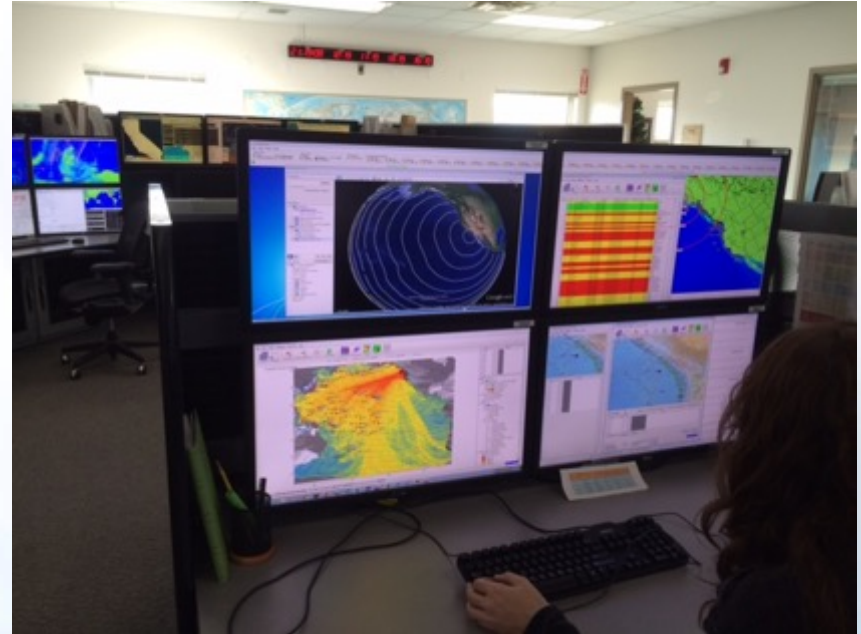
- Initial seismic processing complete and warning issued

20-90 minutes:

- First observation of tsunami on sea level gage

30-100 minutes:

- Forecast based on models with assimilated sea level



Reviewing Progress

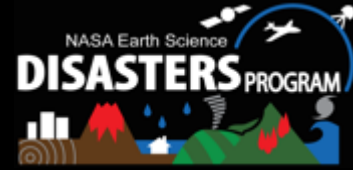
PTWC, Ford Island, HI



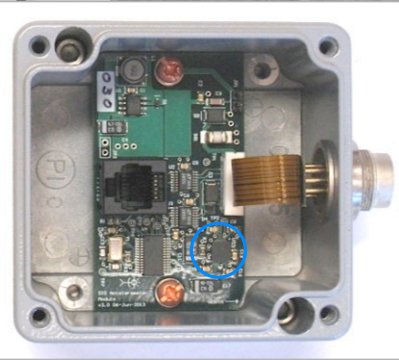
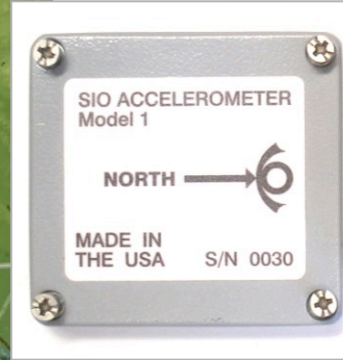
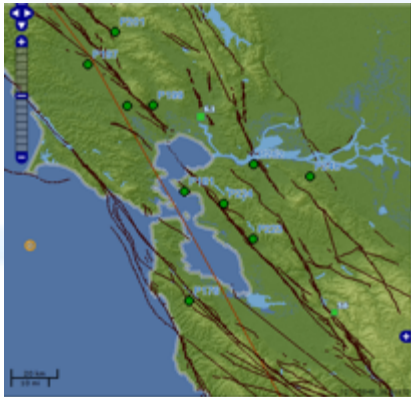
- Compare and understand PTWC process
 - Different computational environment
 - More direct modeling
- Review our efforts
 - Data network established
 - All centers contributing and merging data
 - Demonstrate and Discuss Modules
 - Diagnose data gap/latency issues
- Decide on our path forward
 - Resolve communication issues
 - Install concrete/simple modules



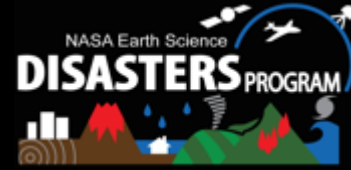
Scripps Institute of Oceanography



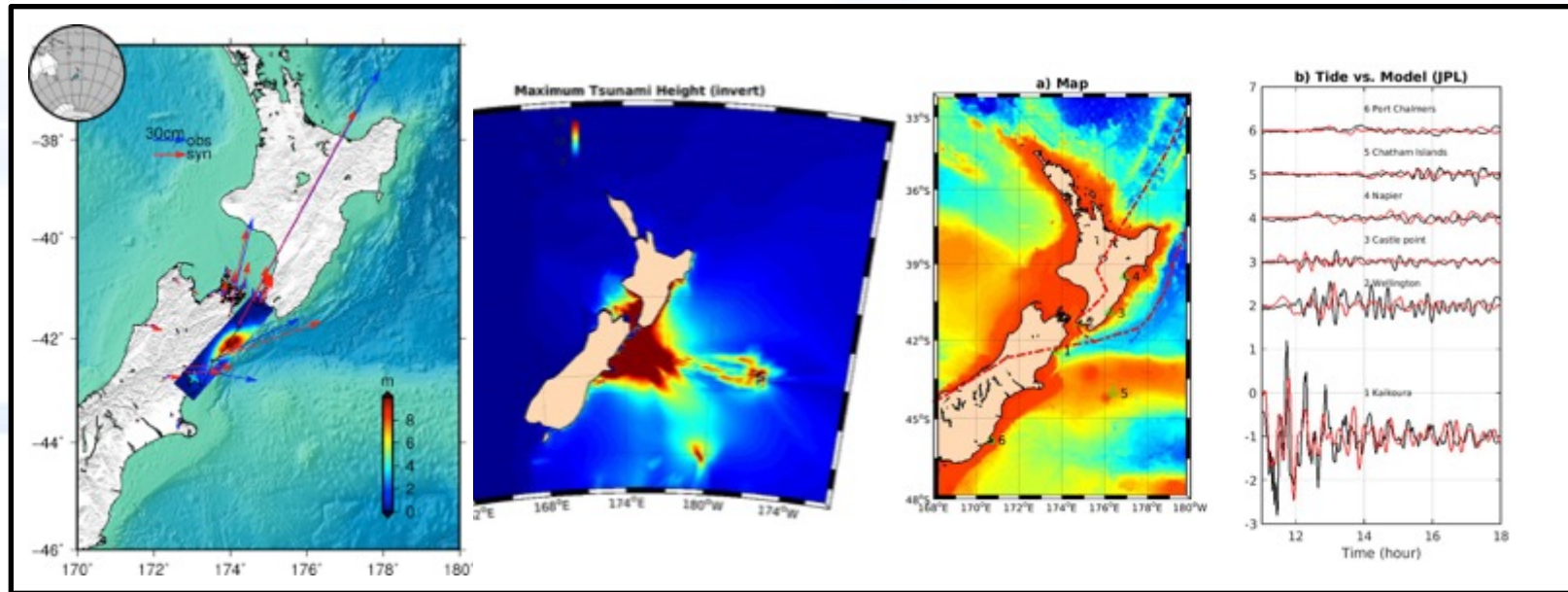
- Leads the Real-Time Earthquake Analysis for Disaster Mitigation (READI) Network
- Developed MEMS Seismogeodetic Sensors
 - Deployed in Bay Area by UNAVCO
 - Deployed in Southern California on SCIGN



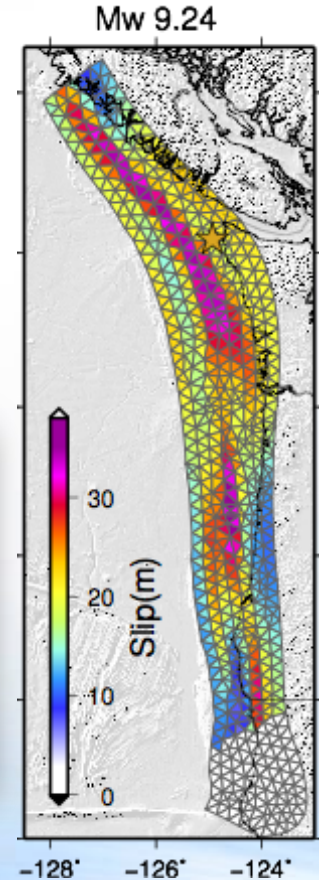
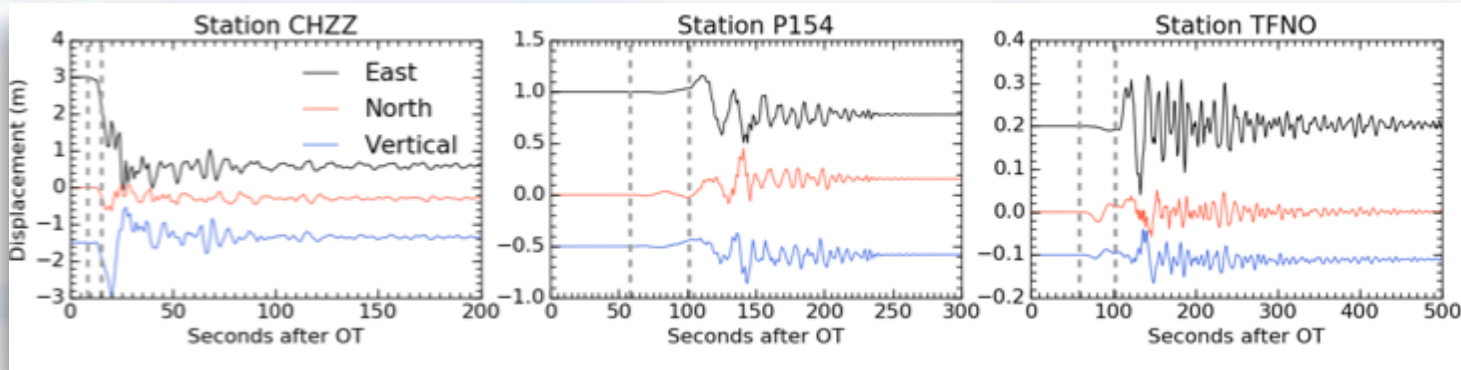
Jet Propulsion Lab



- GPS-Aided and DART-Ensured Real-time (GADER) Tsunami Early Detection System
- Global Differential GPS (GDGPS)
 - 250+ Global and Regional GNSS Stations Currently Served



- Developed *Fakequakes* and Event playback tools
- Contributed to evaluation & testing and exercise participation

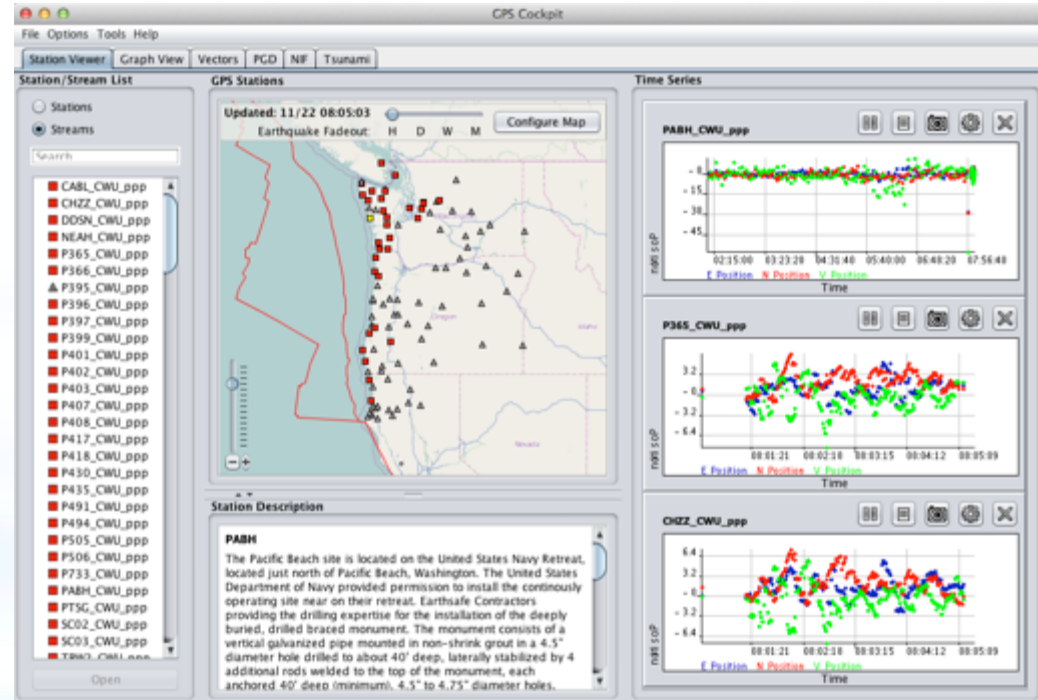


Central Washington University



Contributed and Developed

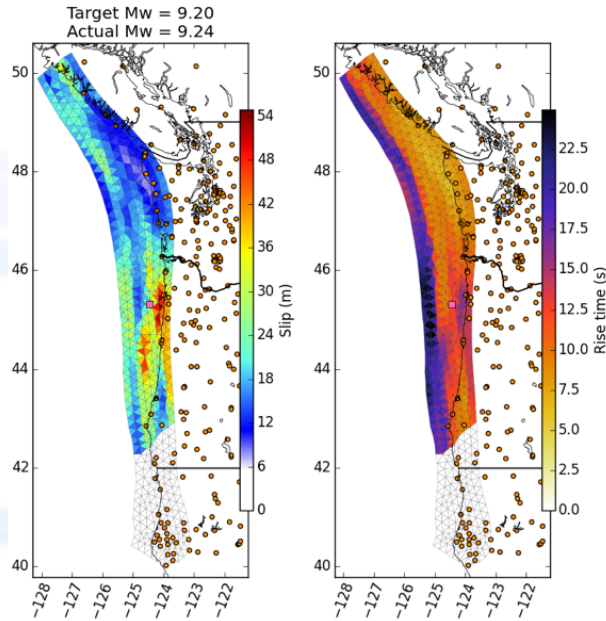
- *RabbitMQ* casting
- Kalman filter based merging of solutions
- *GPS Cockpit* network monitoring
- Cascadia megathrust fault continuous estimation
- PANGA network



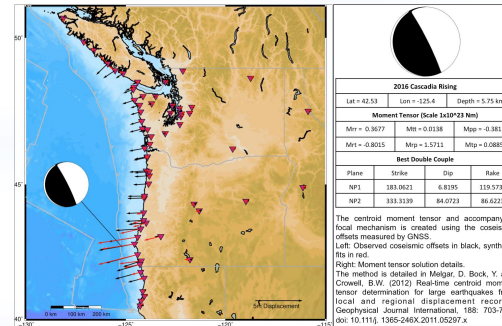
Participation in Cascadia Rising



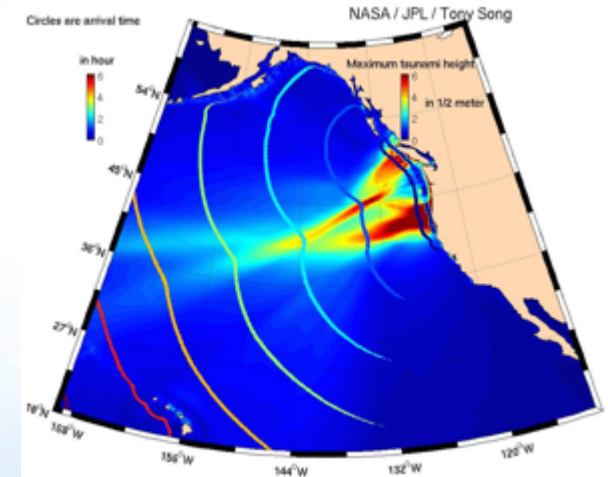
- NOAA and NASA cooperated in developing GNSS tsunami products for testing in the Cascadia Rising National Level Exercise (NLE)



Fakequakes and GNSS Measurements
Melgar, UC Berkeley



Simulated Location and Magnitude Determination
Bock, Scripps



Resulting Tsunami Source Function
Song, NASA JPL

Consistent, Redundant Data Streams

